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DERIVATIONS OF LOAD FACTORS FOR DESIGN OF NUCLEAR POWER PLANT COMPONENTS

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Derivations of Load Factors for Design of Nuclear Power Plant Components*

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Abstract

This paper introduces the concept of probabilistic design of nuclear power plant components and illustrates the methodology and usefulness of the concept with a simple example. It discusses the fundamental relationship between load and resistance factors associated with load combination formats that may be used for design. The simple example consists of a simply supported pipe subjected simultaneously to internal pressure, dead weight and a velocity transient. Associated with each of these loads is a coefficient or load factor whose value is governed by the dispersion of the loading magnitudes and the desired reliability level of the component. The task is to find the optimal set of load factors which results in a design having a specified target reliability.

The load factors were derived using an ensemble of forty combinations of pipe length and diameter and were evaluated for target limit state probabilities ranging from 10^{-2} to 10^{-8}. For the entire array of pipes designed with these load factors (that is, determining their thickness) the actual limit state probabilities ranged from 1.003×10^{-2} for the 10^{-2} target to 1.076×10^{-8} for the 10^{-8} target. The mean limit state probability for the ensemble of pipes designed in accordance with NB.3652 of the ASME Code was 2.571×10^{-3} with a coefficient of variation of 0.859. Designs executed with load factors to meet a target limit state probability of 10^{-3} had a coefficient of variation of only 0.107. This demonstrates that the use of probabilistically derived load factors can result in designs having both assured and more consistent levels of probability.

This methodology, as will be demonstrated in companion papers, can be extrapolated to the design of real components of greater complexity and subjected to multiple dynamic loads. Its usefulness lies in the advantage that designs may be executed using deterministic methods to assure a desired level of component reliability.

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Derivation of Load Factors for Design of Nuclear Power Plant Components

One of the more perplexing problems in structural engineering involves the specification of load magnitudes when a structure is subjected to multiple time varying loads. Building and structural codes resolve this problem for the designer by providing factors for these loads in combination which compensate for the uncertainties in the anticipated load magnitudes over the design life of the structure. Factored load combinations have been incorporated into recent American Concrete Institute (ACI) and American Institute of Steel Construction (AISC) nuclear codes but they have not been completely accepted by the U. S. Nuclear Regulatory Commission (NRC). Instead, the NRC has specified factored load combinations for nuclear structures in the Standard Review Plan (SRP). There are, however, no specifications for load combinations with appropriate factors for nuclear power plant mechanical components. Consequently, there is no universally recognized criterion which can serve as a guide to which loads applied to these components should be combined. Nor is there an incontrovertible criterion for how these loads should be combined.

The design of mechanical components such as piping, vessels, valves, pumps, etc. is governed by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. This code does not specify which loads should be combined. Rather, the philosophy of the ASME code is to place limits on stress which the unfactored load effects (or responses) must not exceed. These stress limits vary in accordance with the service level assigned to a particular load combination. The actual load combinations, however, are formulated by the owner through the design specification required by the code. As a result, the requirement to consider concurrent dynamic events, (Ref. 1) has led to load combination formats based upon judgement and to a situation where safety margins of systems and components vary widely from plant to plant.

It would appear that the design of mechanical components subjected to multiple time varying loads would be facilitated by the application of appropriate factors to the various loads in combination as in the case of structural engineering practice. However, there is too little experience with the responses of nuclear power plant components to combined dynamic loads to assign load factors with a satisfactory degree of confidence. This contrasts with the extensive experience gained by observing the behavior of conventional structures over a wide geographic area for many centuries. This experience with conventional structures includes the observation of failures at all levels of severity from which much has been learned. There is no equivalent repository of experience with nuclear power plant components nor will there ever be if the nuclear power plant industry is expected to survive.

Clearly, if we are to facilitate the design of nulear power plant components for multiple time varying loadings with the aid of load factors, we must apply a more rational procedure than judgement refined by long experience. Even the structural engineering field has recognized shortcomings in the way it assigns load factors. The problem is that safety in design was perceived merely in terms of the conservatism that could be attained by adjusting the design load levels. Actually, safety is a function both of the loading and the strength or resistance of the structural components. The measure of safety, or reliability, can better be attained by considering load and resistance jointly. Studies have been published (Ref. 2, 3) which describe methodologies for generating load and resistance factors on a probabilistic basis. These studies are directed toward code or standards writers engaged in preparing new codes or revising old ones. The intent is to encourage the development of codes that will result in structures of optimum reliability with regard to cost and safety and structures having more consistent levels of reliability.

While the probabilistic methodology described in these studies are applicable to the design of mechanical components, its use must be reconciled not only with the unique loading and material characteristics of nuclear power plant components but also with the philosophy of the ASME code which is universally accepted throughout the nuclear industry. The research at the Lawrence Livermore National Laboratory (LLNL) is directed toward providing the basis for developing a "code" that will specify probabilistically determined load factors for nuclear power plant components. This "code" might be an addition to the SRP which would be used to check the implied reliability of designs submitted for review or, as a basis for design by the industry when they gain confidence in the methodology. While the SRP would incorporate elements of the ASME code, it would not replace it nor be in conflict with it. As a matter of fact, it would seek to preserve the deterministic design format of the ASME code while providing the criteria that reflects the probabilistic approach to design. This implies that the designer need only be concerned with combining the maximum or nominal responses from individual loads as in current practice. The factors associated with the responses or nominal loads are provided by a "code writing" group that specilizes in probabilistic methods in structural analysis and design.

The design format that appears in the ASME Code is expressed as

$$\phi\, S \ngtr Y_1 + Y_2 + Y_3 + \text{----} \qquad (1)$$

where the Y's are the responses (in this case stresses), S is the stress intensity limit for the material, and is a factor whose value is governed by the particular service level associated with the component and the nature of the combined loads. While the relationship expressed in Equation 1. is deterministic, we must be aware that the stresses due to the loads and the resistance of the material are, in fact, random variables. Computed stresses are based upon load magnitudes that have a low probability of exceedance, while the stress intensity limit represents a material resistance having a high probability of exceedance. This is illustrated in Fig. 1 which shows the probability density function for both the combined stress and the resistance and the relative location of the values used for design. Note, however, that there is a finite probability that the combined stresses can exceed the factored stress intensity limit. This is represented by the area under the stress distribution curve to the right of ϕ S. Likewise, there is a finite probability that the resistance of the material can be less than the combined stresses, as represented by the area under the resistance distribution curve to the left of Y. Given the probability density functions of the stresses and the resistance, it is possible to find the probability that the stresses exceed the resistance which is synonymous with the failure probability. Since "failure" may also be associated with loss of function, we prefer the term "limit state probability".

It is also apparent from Fig. 1. that if the design stresses are varied, there will be a shift in the stress density distribution such that the limit state probability will change. This is precisely why arbitrarily selected loads in combination produce a variation in reliability from component to component. On the other hand, if we fix the limit state probability at some acceptably low value, we can, for a specified stress intensity limit, establish a design configuration whose stress levels correspond to a target limit state probability. This may be done with the aid of load factors, each designated by a γ_i . Each set of load factors associated with the responses from individual loads may be optimized to correspond to a target limit state probability. Thus the design format equation takes the form

$$\phi\, S \geq \gamma_1 Y_1 + \gamma_2 Y_2 + \gamma_3 Y_3 \text{ ---} \qquad (2)$$

This is the format that appears in the ASME Code except that the Code specifies unit load factors. It is, of course, possible to apply the probabilistic approach to the ASME Code format by adjusting only the resistance factor, ϕ . However, the advantage of using factors in association with the responses is that it results in more consistent component reliabilities for different limit states and design situations.

Again, it is not the designer's task to determine the probabilistically derived load and resistance factors. He simply adjusts his design to satisfy equation 2. with the assurance that the final design will satisfy the target limit state probability requirement.

The method of deriving load factors will now be introduced with a simple academic illustration. From a practical point of view, a set of load factors should be applicable to as broad a spectrum of design configurations as possible. To simulate this we to provide a factored load combination format that can be used to design an ensemble of simply supported pipes subjected simultaneously to internal pressure, dead weight and a velocity transient. The ensemble consists of forty combinations of pipe diameter and length varying from 10" to 24" in diameter and 10' to 50' in length. A typical configuration of the pipe is shown in Fig. 2.

For each of the pipes we computed the limit state probability implied by the application of NB-3652 of the ASME code. For our hypothetical loads the design checking equation takes the form

$$\phi S_m = C_1 V_0 + C_2 \ell + C_3 p \tag{3}$$

where

V_o = initial velocity transient,(in./s)

ℓ = pipe length,(in.)

p = internal pressure,($lb/in.^2$)

c_1 = influence coefficient which transforms the initial velocity into a bending stress,($lb/in.^2$)/(in./s)

c_2 = influence coefficient which transforms the pipe length into a bending stress,($lb/in.^2$)/in.

c_3 = influence coefficient which transforms the internal pressure into an axial membrane stress, ($lb/in.^2$)/($lb/in.^2$)

S_m = stress intensity limit,(lb/in^2)

ϕ = resistance factor which reflects the stress categories in the load combination

Fig. 1 Statistical distributions of response and resistance

Fig. 2. Schematic representation of a simply supported pipe of length, diameter D and wall thickness, t.

All the parameters except pipe thickness and diameter were considered normally distributed random variables so that the limit state probability can be expressed by

$$P_F = 1-\Phi\left[\frac{\bar{R}-\bar{Y}}{(\sigma_R^2+\sigma_Y^2)^{1/2}}\right] \qquad (4)$$

where

Y $= C_1V_0 + C_2\ell + C_3p$

Φ = Gaussian or normal distribution function for the argument in brackets,

$\bar{R}$ = the mean resistance or strength of the material, corresponding to its assumed failure mode,

σ^2_R = the variance of the resistance,

$\bar{Y}$ = the mean response,

σ^2_Y = the variance of the response.

For the assumed values of the parameters listed in the appendix, the average limit state probability of the forty pipe configurations was calculated to be 2.571 x 10^{-3} with coefficient of variation of 0.859.

We now turn our attention to deriving sets of load factors that correspond to various levels of specified or target limit state probabilities. The design format takes the form

$$\phi S_m \geqslant \gamma_1 C_1 V_0 + \gamma_2 C_2 \ell + \gamma_3 C_3 p \qquad (5)$$

where $\gamma_1, \gamma_2, \gamma_3$ are the load factors corresponding to V_o, ℓ , and p, respectively.

The derivation of load factors is an iterative process which requires the assumption of an initial set of factors. Unit values are as good as any and were the ones used in this example. With these assumed load factors the pipe is "designed" which, in this case, means that the pipe thickness required to meet the ASME code stress intensity limit is established. The limit state probability of the pipe is computed as previously described and the difference between this and the target value, P_T, is recorded. This process is repeated withthe same assumed load factors for all forty pipes and the following function of the disparity between the computed and target limit state probabilities is formulated

$$f(\gamma) = \sum_{\text{All Pipes}} \left[\frac{\text{Log } p_f - \text{Log } p_T}{\text{Log } p_T}\right]^2 \qquad (6)$$

The task now (for the computer) is to modify the assumed and subsequent sets of load factors such that the objective function described by equation 6 is minimized. The set of load factors that emerges is one that is optimum for approaching the target limit state probability over the entire ensemble of pipe configurations. This is illustrated in Table 1 which shows the values of the sets of optimized load factors corresponding to target limit state probabilities ranging from 10^{-2} tp 10^{-8}. Note that for a target limit state probability of 10^{-3} which corresponds closely to the limit state probability implied by the ASME code, the coefficient of variation over the entire ensemble of pipes is 0.107. Using the ASME code rules (without load factors) results in a coefficient of variation of 0.859. This demonstrates that the use of probabilistically derived load factors can result in designs having both assured and consistent levels of reliability.

TABLE 1 Load factors for the case $\phi S_m = \gamma_1 Y_1 + \gamma_2 Y_2 + \gamma_3 Y_3$.

P_T	γ_1	γ_2	γ_3	$\overline{P}_F$	$\sigma(P_F)$	COV
10^{-2}	0.875	0.873	1.034	1.003×10^{-2}	6.000×10^{-4}	0.060
10^{-3}	0.917	0.913	1.122	1.007×10^{-3}	1.076×10^{-4}	0.107
10^{-4}	0.957	0.951	1.197	1.014×10^{-4}	1.632×10^{-5}	0.161
10^{-5}	0.995	0.987	1.263	1.023×10^{-5}	2.282×10^{-6}	0.233
10^{-6}	1.033	1.023	1.324	1.037×10^{-6}	3.051×10^{-7}	0.294
10^{-7}	1.070	1.059	1.381	1.054×10^{-7}	3.970×10^{-8}	0.377
10^{-8}	1.108	1.076	1.434	1.076×10^{-8}	5.099×10^{-9}	0.474

The purpose of the foregoing illustration was to introduce the concept of probabilistically derived load factors, demonstrate the methodology, and indicate some of the advantages that load factors can provide in conjunction with an ASME code design format. Simplicity dictated the use of a quasi-static load combination model. However, when two or more time-varying loads are specified, the probabilistic approach requires that the distributions of the responses to these loads be combined to obtain the distribution of the extreme response. This, combined with the distribution of the resistance, gives the limit state probability of the component subjected to multiple time-varying loads. The load factors for this case are derived as illustrated in the simple example except that the distribution of the extreme response takes into account, in addition to random amplitudes, such things as load duration, mean rate of occurrence, time phase relationships etc. The methodology for generating the distribution of the extreme response for multiple time varying loads is included in a companion paper.

Appendix

Equations and numerical values or the parameters used to derive the limit state probabilities and load factors in the example.

$$C_1 = \frac{4}{\pi}\left[\frac{E}{g}\left(4\Delta_s + \frac{D}{t}\Delta_w\right)\right]^{\frac{1}{2}}$$

$$C_2 = \ell\left(\frac{\Delta_s}{D} + \frac{\Delta_w}{4t}\right)$$

$$C_3 = \frac{D}{4t},$$

where

E	=	modulus of elasticity of pipe material, = 30,000,000 lb/in^2
g	=	acceleration due to gravity, = 386 in/s^2
Δ_s	=	density of pipe material, = 0.3 lb/in^2
Δ_w	=	density of fluid, = 0.026 lb/in^2
t	=	pipe thickness,
D	=	pipe diameter,
S_m	=	Stress intensity limit, = 15,600 lb/in^2
ϕ	=	1.5 for combined primary membrane and bending stress
V_o	=	12 in/sec.
$\bar{R}$	=	30,000 lb/in^2 (yield strength)
σ_R	=	$0.05\bar{R}$ = 1500 lb/in^2
$\sigma(V_o)$	=	$0.10V_o$ = 1.2 in/s
$\sigma(\ell)$	=	0.01ℓ
$\sigma(R)$	=	285 lb/in^2

References

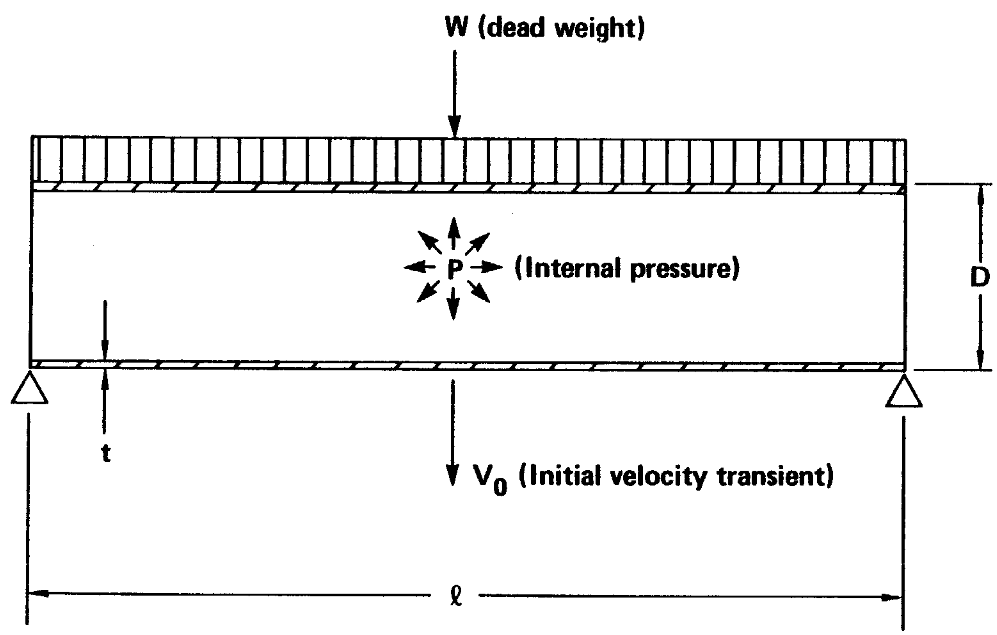
1. 10 CFR Part 50 General Design Criteria for Nuclear Power Plants Appendix A, General Design Criteria 2, Design Bases for Protection Against Natural Phenomena.

2. Ellingwood, B., Galambos, T.V., McGregor, J.G., Cornell, C.A., Development of a Probability-Based Load Criterion for American National Standard A 58, NBS SP-577 #126 File 410-99, April, 1980.

3. Rationalization of Safety and Serviceability Factors in Structural Codes, Construction Industry Research and Information Association Report 63, London, July 1977.

List of Figures

LOAD COMBINATION CONFIGURATION FOR SIMPLY SUPPORTED PIPE EXAMPLE



35 mm
crop marks

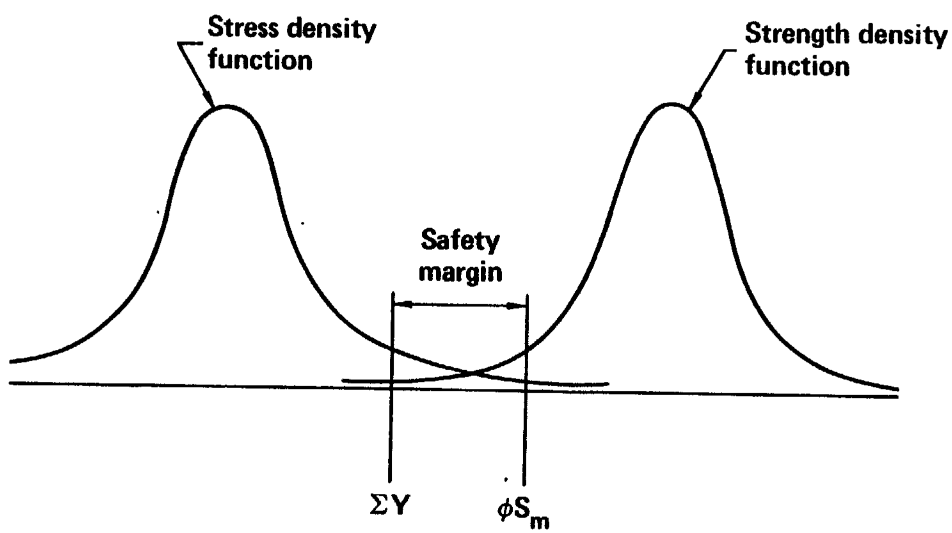
Size Vu-graphs ______ % Prints ______ %

If color if to be added

- Make a stat or film positive of the finished line art
- Add the color to the stat or positive and bleed any color background to this border

Vu-graph crop marks

STATISTICAL DISTRIBUTION OF STRESS AND STRENGTH



35 mm crop marks

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